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# Tailoring the photonic band gap of a porous silicon dielectric mirror

V. Agarwal[a] and J. A. del Río[b]
*Centro de Investigación en Energía Universidad Nacional Autónoma de México AP 34, Temixco, Mor. CP 62580, México*

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A systematic method to fabricate porous-silicon one-dimensional photonic crystals has been engineered to have a photonic bandwidth up to 2000 nm. The observation of the tailorability of the photonic band gap (PBG) underscores the requirement of the large refractive index contrast for making broad PBG structures. In this letter, we present the fabrication and characteristics of such structures that may be promising structures for a large variety of applications. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1559420]

Dielectric mirrors can reflect light for any direction of propagation in specific wavelength regions.[1–4] This property will allow the creation of all-optical integrated circuits as it can be used to confine, manipulate, and guide the photons. The advantage of a dielectric mirror over metallic ones is due to the dispersive and absorbing regions in the visible and infrared spectra of metals.[5] These kinds of dielectric photonic-band-gap (PBG) structures have already been used in vertical-cavity surface-emitting lasers,[6] dielectric interference filters,[7] sensors,[8] and other devices.

Alternating layers of material with different dielectric constant are the simplest possible photonic crystals known so far. These dielectric multilayer films act as a perfect mirror for light with a frequency within a sharply-defined gap. For a fixed number of periods, the PBG increases as the ratio of the refractive indices of the two layers [$n_H/n_L$, high ($H$) and low ($L$) refractive index $n$] increases,[1,9] and, for a fixed ratio of refractive indices, up to a certain limit, the PBG increases with the number of periods.[9] In this letter, we propose an idea to tailor the PBG structures, ranging from a few nanometers to 2000 nm or more, for two different values of refractive indices, ($n_H$,$n_L$) without the prerequisite of a huge contrast. The idea has been implemented experimentally on porous silicon.

Porous silicon (pSi) is already considered as a promising material for photonic applications.[10] This material can be fabricated with electrochemical etching of silicon with HF. In this material, the porosity is a linear function of the current density for a specific HF concentration and anodization time,[9] and is known to show a refractive index contrast for different porosities.[11] Therefore, a periodic pulse alternating between two different current densities has been a convenient procedure to fabricate multilayer pSi films.[9,10,12] The change of the current density does not affect the previously formed pSi layer because silicon dissolution occurs at the silicon–electrolyte interface.[13]

The multilayer pSi one-dimensional PBG structures known until now have a PBG of less than 500 nm.[9,10] What we require is an easy method to modify the PBG of the structure according to our requirements. This letter describes a technique to tailor PBG structures materialized on pSi multilayer mirrors. Stacks of $\lambda/4$ ($n_H d_H = n_L d_L = \lambda/4$, with $d_i$ being the real thickness) mirrors have been prepared for different wavelengths in the visible and near-infrared (NIR) regions (one submirror after the other submirror). The number of submirrors fabricated in a single structure varies from 2 to 80. Each mirror is designed for a different wavelength and can consist of 2.5 to 20 periods, according to the requirements and the region we want to work with. Thus, the number of pSi layers can go up to 700. The exact selection of the $\lambda$-values depends on the application, which will be discussed in the latter part of the letter.

Our method has been inspired by the ladder structure simulated by Kavokin *et al.*[14] in order to observe photonic Bloch oscillations. The structures proposed are coupled microcavities, but here we present the structures without cavities, considering only dielectric Bragg mirrors (DBM). Of course, ladder structures can be prepared by different techniques, for example, by molecular-beam epitaxy, metal oxide chemical vapor deposition, etc. However, in this letter, we use a cheap, easy, and fast technique to produce the same.

We have fabricated pSi multilayers by wet electrochemical etching[15] of highly boron-doped substrate ($p+$, 0.001–0.005 $\Omega$ cm). In order to have better interfaces, an aqueous HF/ethanol/glycerol electrolyte with 15% HF, 75% ethanol, and 10% glycerol[16] concentration is used to anodize the silicon substrate. In addition, in order to maintain a constant HF concentration over the interface between Si and pSi under chemical attack, during the etching process a peristatical pump is used to circulate the electrolyte within the Teflon™ cell. Anodization begins when a constant current is applied between the silicon wafer and the electrolyte by means of an electronic circuit controlling the anodization process. To stabilize the pSi multilayer structure, all the samples are thermally oxidized in an oxygen ambient at 900 °C for 10 min.[17] Oxidation induces a blueshift in the peak reflectivity due to the decrease in the refractive indices of the layers. In our structures, the multilayers have alternating porosities of the order of 35%–55%($n_H$) and 60%–85%($n_L$). The time taken in the etching process varies from few minutes to 3 h. Hence, to make the surface stable, the first layer is always a low-porosity layer and made 10–20-nm thicker than usual

[a]present address CIICAp-Universidad Autónoma del Estado de Morelos, Av. Universidad 1001, Col Chamilpa, Cuernavaca, Mor, México
[b]Electronic mail: antonio@servidor.unam.mx

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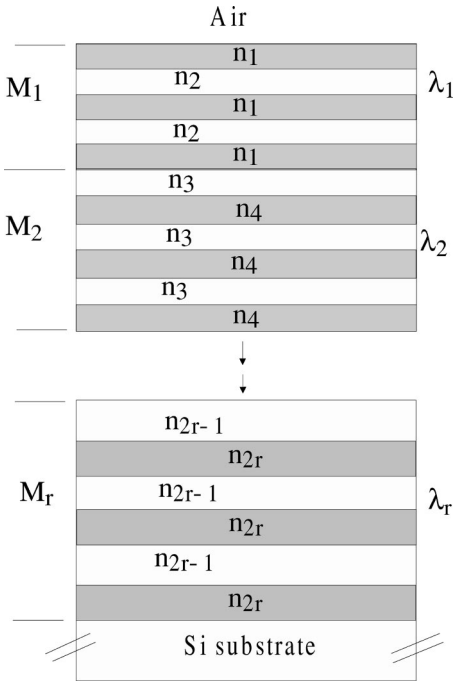


FIG. 1. Schematic draw of the proposed structure. The arrows indicate the direction of the etching process, $i=1,2,\ldots r$ indicates the number of λ/4 submirrors in the complete structure. The number of submirrors depends on the desired range of reflection. The number of layers present in each submirror affect the flattness of the PBG. $n_i$ represents the refractive index of each layer. The refractive index contrast $n_{2i}/n_{2i-1}$, can be different/same for different submirrors.

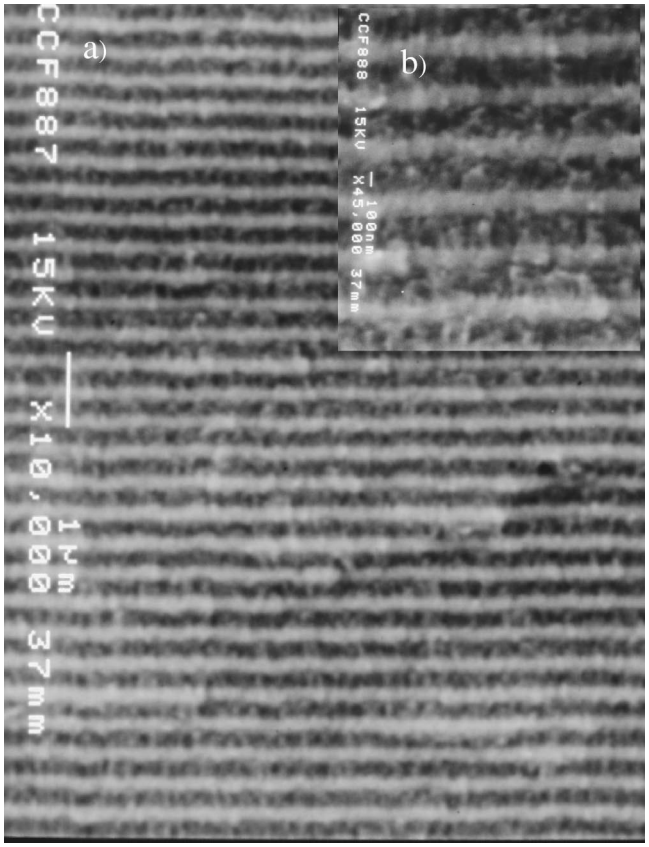


FIG. 2. Cross-sectional SEM image of a mirror designed for partial visible and complete NIR region. Inset shows an amplified view of the structure.

for thick structures (more than 20 $\mu$m). The refractive indices of the pSi layers have been estimated using reflectivity spectra of 2-$\mu$m-thick single layers at 1500 nm. Scanning electron microscopy (SEM) was used to examine the structural features of the films. The reflectivity spectra of the samples are taken with a Shimadzu UV3010 ultraviolet–visible–NIR (UV–vis–NIR) spectrophotometer at 5° incidence.

The schematic of the structures can be seen in Fig. 1. The idea is to make one submirror after another submirror, like a continuum array of submirrors. The specific range of λ-values depends directly on the application. Consider, for instance, a mirror reflecting the complete NIR range (800 to 2500 nm) only; for this we need to select the different wavelengths in this specific range in a way that the PBGs of respective submirrors overlap and give us a continuous PBG reflecting the full NIR range. In designing the mirrors for the latter part of the visible region and the NIR region, we have empirically selected the λ-values as follows. First, select the starting $\lambda_1$-value, then, the subsequent λ-values obey a simple relation $\lambda_{i+1}-\lambda_i=2+i$, where $i$ represents the submirror number. This selection has been performed and shown in the latter part of the letter.

We have made various structures composed of a single mirror with 10 periods (one period consists of one low-porosity and one high-porosity layer) up to a mirror composed of a set of 80 submirrors. The total number of layers varies from 20 to 650, respectively. Taking into account that in the wide PBG structures the anodization time is of the order of hours, to make the structure more stable the first mirror always starts with a high refractive index layer, consisting of 2.5 to 4.5 periods. The subsequent submirrors consists of 3 to 5 periods, reducing the etching time without affecting the flatness of the PBG.

Figure 2(a) shows cross-sectional SEM images of 9 out of the 54 submirrors in the complete structure designed for the partial visible and complete NIR region. This image shows a continuum array of submirrors prepared using $\lambda_{i+1}-\lambda_i=2+i$, designed by taking $\lambda_1=700$ with a refractive index contrast given by $n_L/n_H=1.4/2.2$. The reflectance spectrum of this structure is shown in Fig. 3(b).

The absolute reflectance spectra of some of the structures have been shown in Fig. 3. The absolute reflectivity of commercially available aluminum (Al) mirrors with a SiO overcoat (as bare silicon is prone to oxidation and loses its reflectivity) is shown in Fig. 3(a).[18] The figure clearly shows an absorption in the visible region. From 400 to 2500 nm, the reflectivity varies between 85% and 90%, with a dip to 75% at around 825 nm. Taking this mirror as a reference (available with the Shimadzu UV3101 UV–vis–NIR spectrophotometer) the reflectivity spectra of our structures have been measured. Hence in the visible region, the reflectance shown by most of our structures was higher than that for the Al mirror. Thus, the data have been corrected for the Al mirror response. Figures 3(b)–3(d) show the absolute reflectance of few examples, demonstrating the implementation of the idea. In Fig. 3(b), we present the response of the mirror shown in Fig. 2. It has the PBG for the partial visible and complete NIR region; that is, from 615 to 2450 nm. The absolute reflectance can be clearly seen within 85%–100%, which is clearly 2%–20% more than that for the Al mirror from 615–

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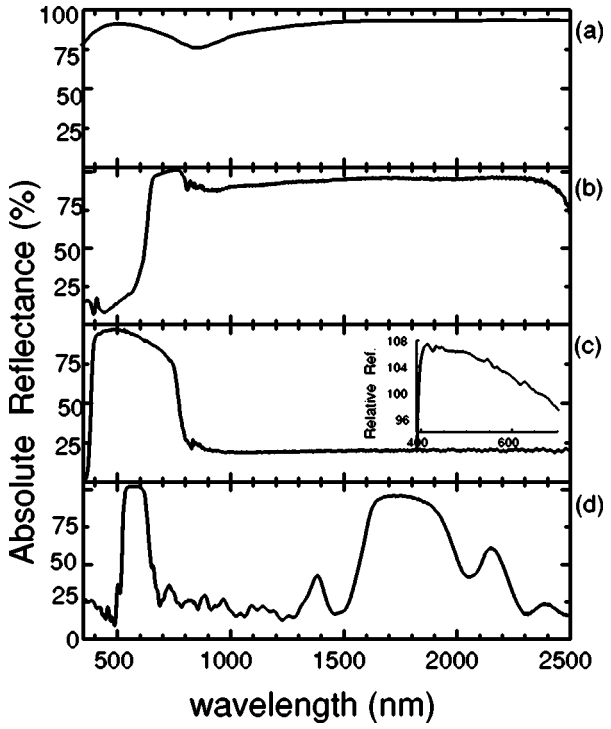


FIG. 3. Absolute reflectance vs wavelength for (a) commercially available Al mirror with SiO overcoat; (b) partial visible and complete NIR region mirror made of porous-silicon multilayers (refractive index contrast: 1.4/2.2); (c) complete-visible-range mirror made with refractive index contrast 1.4/2.2, inset showing the relative reflectance of this mirror with respect to Al; and (d) a discrete mirror designed for 600 and 1700 made with refractive index contrast 1.4/2.2 and 1.5/2.0, respectively.

1200 nm. In Fig. 3(c), we plot the absolute reflectance of a mirror designed for the complete visible range. The absolute reflectance of this mirror is higher than the Al mirror from 390 to 650 nm range, as can be seen from the inset, which shows the raw data coming from Shimadzu UV3101 UV–vis–NIR spectrophotometer, having the Al mirror as reference. This mirror is composed of 77 submirrors, with the starting wavelength 450 nm and the subsequent DBMs are determined by the relation $\lambda_{i+1}-\lambda_i=3$ having 4 periods in each submirror. The refractive index contrast used was 1.4/2.2.

The reflectivity of a mirror reflecting two different wavelength ranges has been shown in Fig. 3(d). This particular mirror is composed by two submirrors, one prepared for 600 nm ($n_L/n_H=1.3/2.3$) and another for 1700 nm ($n_L/n_H=1.6/2$) with 10 periods each. The idea is to show how we can change the refractive index contrast from one submirror to another submirror if required. Theoretical simulations have been done for all the tailored PBG structures and seen to be in agreement with the experimental reflectivity spectra[19]

Here, we can clearly see the enhancement of the PBG width with the increase in the number of submirrors. We can very well understand that this broad PBG is due to the overlapping of all the PBGs of the submirrors designed for different wavelengths. The advantage of these mirrors over metallic mirrors (Al or silver) is their selective nature and higher reflectivity. For example, designing a mirror for the complete NIR range without significant reflection from the visible range or vice versa will be excellent for different applications.

It is important to stress that Pavesi group, too, has developed photonic structures with wide PBG using aperiodic porous-silicon layers.[20]

Apart from the structures shown in Fig. 3, we have tailored the PBG for many other mirrors, for example, in the spectral ranges of 356 to 650, 400 to 600, 600 to 1200, 600 to 2000 nm, etc. The idea is to design a PBG of desired width and at required wavelengths. Here, we present just few examples with a lot of scope for improvement. It will also stimulate interest in making better filters based on a single microcavity,[21] because with the method presented here we are able to increase the high reflecting range on both sides of the cavity.

We have shown, in this letter, that it is possible to tailor the PBG of the dielectric mirrors, for the partial UV and complete vis–NIR range (from 356 to 2500 nm) to have desired width at required wavelengths. These mirrors are easy to prepare, selective, and more reflective than the commercially available Al mirrors.

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